

A MICRO TURBINE POWER SOURCE FOR DEEP-SPACE APPLICATIONS

Final Report

JPL Task 1027

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A. OBJECTIVES

The problem addressed by the proposed work is to develop a Micro-Electromechanical-Systems-based meso-scale power supply to meet requirements for deep-space power. The device proposed to satisfy this requirement is a 9-cm³ MEMS-based turbine generator producing up to 50 Watts of electrical power, operating with a closed cycle of xenon at 10 atmospheres pressure, capable of operation with internal combustion, concentrated solar radiation or radionuclides as the heat source. The deep-space environment is intrinsically challenging for power sources since the solar-radiation flux for power generation is low, and the extreme cold creates problems for the kinetics of electrochemical-based systems such as batteries, and readily freezes the water present in fuel cells. Mass and volume are at a premium as well. These issues suggest a power source with high energy and power densities capable of operating at extremely low temperatures.

Internal combustion devices represent about an order of magnitude improvement in energy density over batteries. The turbine generator described in this proposal, consuming around 15 gm/hr of 10 kWhr/kg fuel, represents an energy density of 1.7 kWhr/kg, which includes the fuel for 1 hour of operation. This compares with about 0.3 kWhr/kg for macro-scale primary Lithium batteries. The recent development of a 3D LiGA (X-ray-lithography-based micro-fabrication technology) capability at JPL will enable the precision fabrication of the highly miniaturized turbine-based power generator.

The proposal listed two basic objectives with four sub-objectives. They are:

- 1) Globally, to develop a 9-cm³ MEMS-based turbine generator producing up to 50 W of electrical power. It will operate with a closed cycle of xenon at 10-atmospheres pressure. The initial plan incorporates an internal combustion heat source.
- 2) The DRDF seed money here is for the development and demonstration of critical basic concepts of design and fabrication of this device. These include:
 - a) Design and fabricate a meso-scale closed-cycle turbine demonstration unit at a scale manufacturable using conventional high-precision fabrication technologies.
 - b) Characterize the performance of a closed-cycle demonstration unit.
 - c) Design and fabricate, for concept demonstration purposes, a representative turbine using 3D LiGA.
 - d) Prepare a final report documenting all findings and results of the project.

B. PROGRESS AND RESULTS

The tasks for this project were divided up between JPL and Dr. Phil Muntz's group at USC. The initial design was done collaboratively between both groups. The figure below represents the initial concept of the miniature turbine (fig #1)

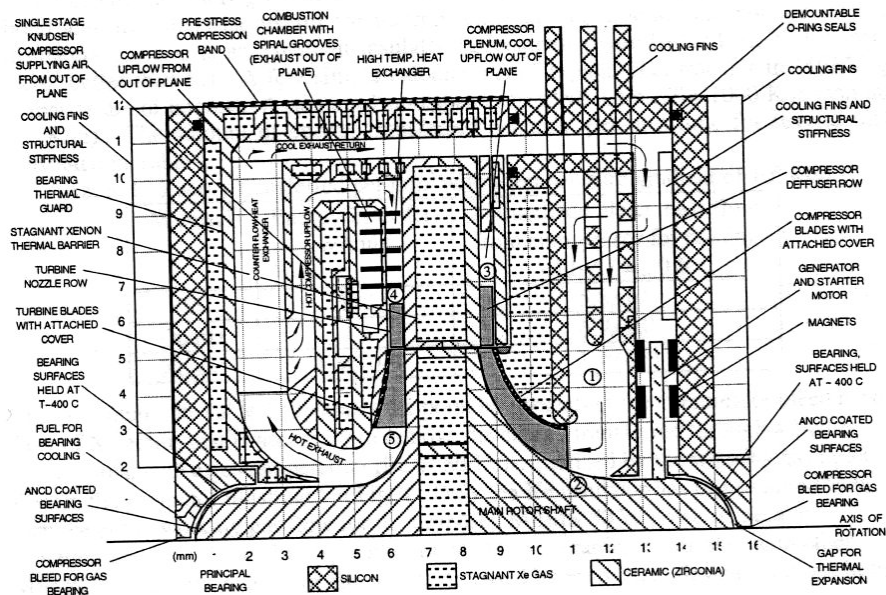


Figure 1: Schematic of Miniature Turbine Power Source

This design incorporates a single shaft for the turbine and compressor, and bearings coated with Argonne nanocrystalline diamond (ANCD). It also has an initial design for the thermal management system. This system, however, needs real data from test runs to go from the initial design stage to one that will work with real components. Because of the complexity of the device, design and fabrication are interrelated, and both will progress in iterative steps towards a final device.

JPL was tasked with the process design for 3D LiGA, and management of the project. USC was tasked with the construction of the test-bed facility, design and fabrication of the demonstration unit, and test measurements.

3D LiGA Processing

LiGA (**L**ithographie **G**alvanoformung **A**bformung: a German acronym meaning lithography, electroplating, and mold-making, describes the processing steps involved in this technology) has become an important approach for making precise micro- and meso-scale parts for many systems on all scales. In brief, the long polymer chains in a high-molecular density acrylic (PMMA: polymethyl methacrylate) are broken up by exposure to soft X-rays generated by a synchrotron source. The acrylic is patterned by masking (blocking) some of the X-rays with a patterned gold mask. The acrylic is then placed in a developing bath to remove the “exposed” acrylic, leaving the unexposed material in the desired pattern. The acrylic is then used as a mold for electroplating (fig #2).

One objective of this project is to expand LiGA technologies into the area of 3D parts using inverse tomography. Traditional LiGA parts are called “2-dimensional” because parts are only patterned in the x-y plane. The z dimension is always a straight vertical sidewall (fig #2).

However, tomography, the ability to reconstruct 3-dimensional objects using 2-dimensional projections, is a natural solution to the problem of fabricating 3-dimensional LiGA parts. In theory, by using multiple masks and dynamic, multi-axis scanning techniques, exposed and developable areas within a substrate can assume arbitrarily complex shapes.



Figure 2: The LiGA Process

The development of a full 3D LiGA capability was broken down into several stages. Initially we focused on creating parts with angled sidewalls using a multi-scanning approach; one scanner for translation and one for rotation (fig #3 and #4).



Figure 3: Translational Scanner

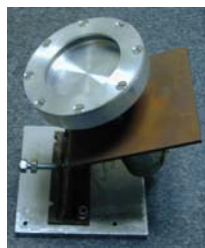


Figure 4: Rotational Scanner

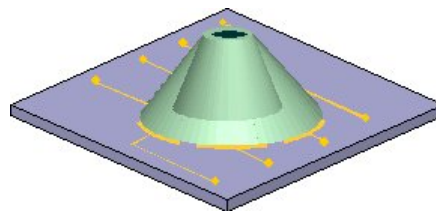


Figure 5: Proposed 3D part

The rotational scanner is mounted on the chuck on the front of the translational scanner to achieve a complex scanning pattern in the path of the beam. Figure #5 shows the design of the intended 3D LiGA part. Figures #6-8 show the results of this initial effort. Figure #6 is an ultra-thick PMMA substrate mounted on a plating base consisting of a silicon wafer coated with titanium-copper-titanium. Figure #7 is a close-up of the exposed and developed substrate, showing the bottom of the inverted cone. Figure #8 shows the electroplated cone before the PMMA is dissolved away.

Because of the complexity of the proposed turbine blades, another intermediary step was undertaken in the development of 3D LiGA. One of the limiting parameters in LiGA is the

thickness of the PMMA films. JPL has successfully researched and fabricated parts using ultra-thick films, with one goal: to find the film-thickness limits inherent in X-ray exposure and development of PMMA, while maintaining precision. In the final stage of full inverse-tomographic LiGA processing, this limit in film thickness will translate into maximum part size. However, for this project, a novel method of “stacking” several PMMA films to create one part is being tried to get around these limits in size. Figure #9 shows the initial design of a compressor to be fabricated using this “stacking” approach. In this process, 5 different substrates, all exposed using the 3D multi-scanning system developed in the earlier process development stage, are made and then combined in a stack prior to electroplating (figure #10) on top of a “core” that has been conventionally machined.

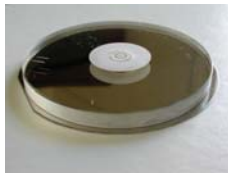


Figure 6: Exposed and developed substrate



Figure 7: Close-up of micro-mold ready to be electroplated.

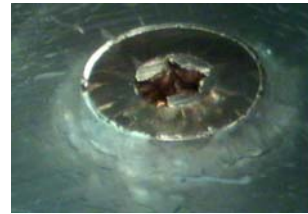


Figure 8: Electroplated cone

Figure #11 shows the actual core and the exposed PMMA substrates prior to electroplating. Prior to electroplating, a new plating chuck is being designed and fabricated, building on our experience with electroplating “unbonded” PMMA (PMMA not bonded to a plating base prior to exposure). This chuck will apply pressure to hold the parts in place and prevent the flow of the electroplating solution into unwanted areas.

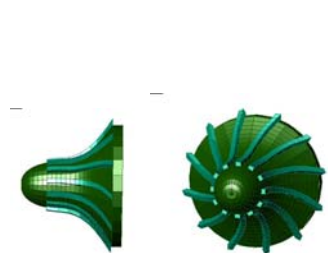


Figure 9: Compressor design

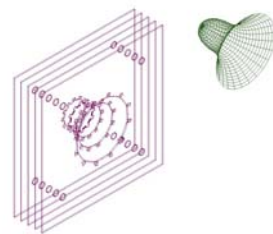


Figure 10: Stacks of PMMA and machined core

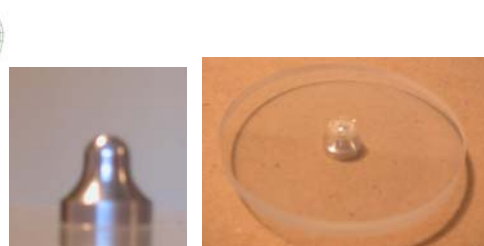


Figure 11: Core and stacks of PMMA mounted on core.

Finally, the results of our experience in the prior stages of research is being incorporated into a final design of a new LiGA scanner which will be programmable along 3 axes of translation and 3 axes of rotation to achieve not only full inverse tomography, but parts that are able to be designed and fabricated in stages to be “stacked” prior to electroplating. This will greatly enhance the range of possible parts addressable by LiGA technology.

USC: Test Bed and Demonstration Device

Figure #12 shows the design of the demonstration “test bed” device for this project. It consists of two basic stages of a turbine and a compressor connected by a shaft, as well as the heat-exchanging system. The shaft originates in a motor/generator to drive the system. The purpose of this setup is not only to demonstrate the concept, but to produce data that can be fed back into the final designs of the turbine, the compressor, and the thermal-management system.

The gas used will be xenon in a closed system. Xenon will reduce the required rotational speed to approximately one-half that required by air for efficient operation. It will also operate at 3-10 atmospheres, which will significantly increase the Reynolds Number, thus increasing the efficiency by an order of magnitude over air.

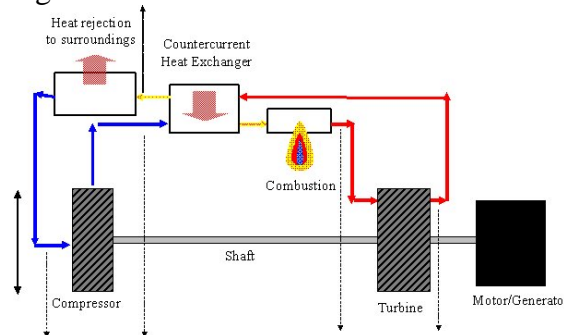


Figure 12: Diagram of the test bed setup

Figure #13 is a spreadsheet that shows both real and estimated performance parameters for the compressor stage. The real performance data was measured from a small compressor, with a diameter of 2 cm, that was used as a model for the design of the miniature version. The projected estimates are for miniaturized versions of the same design. These estimates show that by reducing the size of the compressor by a factor of 2, to a 1-cm diameter, a net power output of 787 watts can be projected. And by reducing it 4 times to a diameter of 0.5 cm, the size required for this project, we can expect a power output of 242 watts, 4 times the power of the project specifications of 50 watts.

							Approx Inlet	Approx Outlet		
compressor diameter	Estimated Pressure		Outlet Stag.		Compressor	Re (Based on tip radius,	Re (Based on tip radius,	Assumed	Assumed	
(cm)	RPM for M	Ratio	Mdot (kg/s)	Temp	Efficiency	Po1=5 atm)	Po3=9.5 atm)	Temp after heating	temp after turbine	
0.5	700000	1.9	0.01	362	399	0.95	2.40E+05	2.85E+05	1200	1050
1	350000	1.9	0.04	375	414	0.87	4.80E+05	5.70E+05	1200	1050
2	175000	1.9	0.15	380	421	0.82	9.60E+05	1.10E+06	1200	1050
Assumed Pressure										
compressor diameter	ratio across turbine	Turbine Efficiency	Power Draw by compressor	Power output by turbine	Net Power Output (W)	Exhaust Recupe. Efficiency	Preheated Gas Temp	Power Req'd to Heat to 1200 K (W)	Combustion Heat Transfer Efficiency	Fuel Consumption g/hr
0.5	1.9	0.95	142.55	384.95	242.40	0.75	887.25	467.96	0.65	71.99
1	1.9	0.87	622.32	1409.40	787.08	0.75	891	1848.40	0.65	284.37
2	1.9	0.82	2641.40	5314.30	2672.90	0.75	892.75	7352.70	0.65	1131.18

Figure 13: Measured and projected power estimates for compressor

Scaled down compressors have been fabricated using a material called “alginate.” This material will shrink down isometrically with water evaporation, thus duplicating a part on a smaller scale. This scaling down can be done multiple times, with each reduction scaling it down by approximately a factor of 2.

Using this reduced-size compressor, an assembly was constructed with the compressor, a diffuser plate, and volute (figure #14).

The test-bed design for the compressor and turbine are shown in figures #15 and #16. These parts will be tested separately, and then combined into one closed-system experiment. Although pictures of the test bed are not currently available, the compressor test bed has been constructed, and experiments and measurements will commence soon. The test bed for the turbine is partially constructed, and will be finished soon.

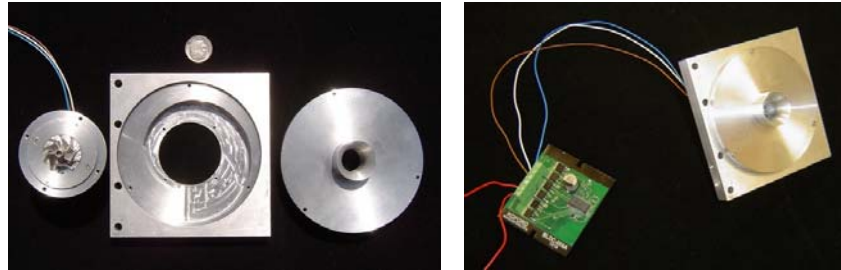


Figure 14: Compressor, diffuser, and volute assembly

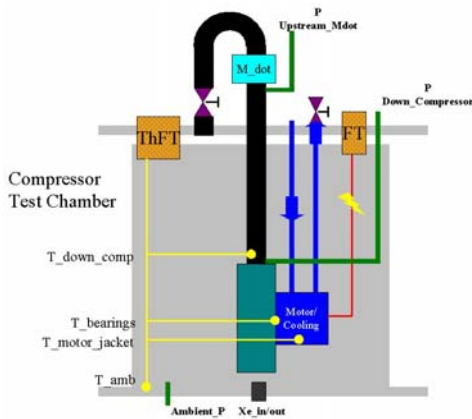


Figure 15: Test setup for compressor

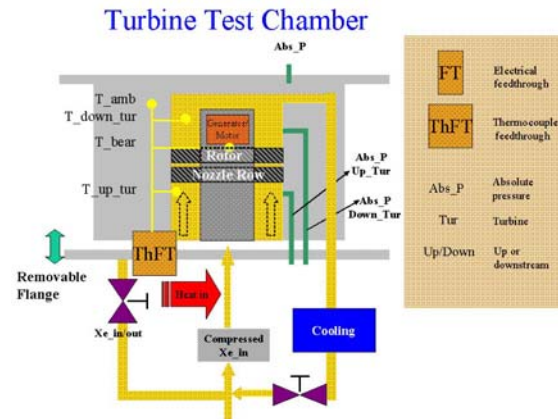


Figure 16: Test setup for turbine

C. SIGNIFICANCE OF RESULTS

Although a final device has not been constructed, significant progress and results have been achieved towards the project’s objectives. A miniature turbine system has been designed, and steps toward its fabrication have been designed and implemented. These include a larger-scale demonstration device for the purpose of proving the concept and gathering data for the smaller-scale version. The process of fabricating parts using 3D LiGA techniques has been demonstrated by fabricating parts with non-straight sidewalls using multi-scanning. Stackable PMMA substrates have been made, each substrate having a different mask to be later combined

into one single part. And finally, designs for possible 6-degree-of-freedom programmable scanners for inverse-tomographic LiGA have been made, ready to be constructed.

A larger-scale demonstration compressor has been fabricated and assembled with a diffuser and volute, and mounted into a test setup. The test setup for the turbine has also been partially constructed, and is close to being ready for active measurement. Measurements of the model compressor have been taken which show that, with a similar blade geometry, it is realistic to project a successful power output of over 50 W.

D. FINANCIAL STATUS

The total funding for this task was \$125,000, all of which has been expended.